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Hot Carrier in Subpicosecond Photoconductive Experiments

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Submitted to
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Summary Abstract

The goal of this program was the development and use of models of femtosecond photoconductive experiments as probes of hot carrier transport in semiconductors. Prototype experiments were being carried out in a companion effort directed by Dr. Gerard Mourou at the University of Rochester, Rochester New York. The Arizona State University modeling effort was directed at several main components to the modeling of such experiments. One must first model the generation of electron-hole pairs inside a semiconductor as the result of the incidence of a femtosecond optical pulse. Then one must model the processes by which the resulting current transient is developed. Lastly, the conversion of the current transient into a voltage wave transmitted down a transmission line must be understood. It is this voltage wave that is directly measured in the experiments of interest. Successful models of all three components were developed.

Statement of Work

In 1972 Ruch [1] suggested that electron drift velocities in submicron FETs could substantially exceed the expected steady-state value and that this could lead to improvements in the device performance. Since that time hundreds of papers have been presented which modeled such high velocities but very few and perhaps no clear unambiguous experimental studies of such transport transients have been presented. This situation arises from the very short picosecond and sub-picosecond time scales required for such studies. In the 1980's advances in electro-optics presented us with such experimental opportunities. During the reporting period we worked cooperatively with an experimental group, directed by Dr. Gerard Mourou, at the Laboratory for Laser Energetics of the University of Rochester, in an effort at using subpicosecond photoconductive experiments as probes of subpicosecond hot carrier transport in semiconductors. Both efforts have been supported through grants from the Air Force Office of Scientific Research, with the Arizona State University effort under award number AFOSR-84-0290.

In these experiments femtosecond laser pulses are used to suddenly turn on a photoconductive switch. This in turn triggers a voltage wave which is transmitted along a microstripline. By using a second delayed pulse it is possible to electro-optically sample the temporal behavior of this wave. The rise-time can be measured with subpicosecond resolution and it appears that changes in the risetime with bias as small as 0.025 picoseconds can be measured. Both portions of the experiment are done on a subpicosecond scale thus making it the first direct probe of subpicosecond current transients in semiconductors. It differs from the vast majority of optical experiments in that information directly pertinent to the carrier momentum is collected whereas spectroscopic techniques tend to probe only carrier energy.

Unlike the situation envisioned by Ruch, where an electric field is suddenly applied to already generated carriers, here we photogenerate carriers in an already extant field. Early variations on this have been reported by Mourou et et al. [2] as an early result of this program, with a similar experiment being reported nearly simultaneously by Hammond [3]. In both experiments a gap was left in a transmission line on top of a semi-insulating GaAs substrate. The pump pulse was focused on the gap and as the photocurrent in the gap evolved a time varying voltage wave was sent down the transmission line. The analysis of Auston [4] was used in both experiments to explain why a photoconductive overshoot should produce a transmission line overshoot. The two experiments both used 620 nm wavelength pumps and differed primarily in the temporal resolution of the measurement of the voltage wave. Hammond used an ion-bombarded second gap as a high speed photoconductive sampler while Mourou et al. abutted an electro-optic sampling crystal against their sample, extended the transmission line onto this sampling crystal and used a second pulse to electro-optically sample [5] the voltage wave. The temporal resolution of Hammond was about 6 ps. which complicated his interpretation. However his results were consistent with the general idea of having no overshoot at very low fields, a temporally extended overshoot (lasting several picoseconds) at medium fields and a temporally sharp overshoot at high fields. Mourou et al. had temporal resolution of about 0.5 ps. and clearly saw an voltage overshoot very similar to the velocity overshoots of Ruch.

There are important complications in analyzing both of these experiments. First, in both cases there is an impedance discontinuity between the photoconductive gap and the sampler. The second is that it is unlikely that good ohmic contacts and uniform fields were attained in either system. The analysis was additionally complicated by the use of semi-insulating GaAs. While it is clear that a photoconductive overshoot occurred it cannot be unambiguously associated with a velocity overshoot.

All of these complications were eased during the latter portions of this program when the experimental group studied switches made of high quality epitaxially grown material [6,7] and utilized an improved electro-optic sampling geometry [8]. The resulting data clearly showed a voltage overshoot whose timescales and bias dependency were those expected if a transport induced velocity overshoot was present in the photocurrent. However, complications yet remain in the analysis of this data and we therefore cannot yet claim to have seen a velocity overshoot.

There are three main steps which must be performed in the development of a model of this experiment. First, we must accurately model the processes by which the laser pulse is converted into electron-hole pairs inside the gap. Secondly we must model the ensuing transport transients and their conversion into a current transient seen at the gap terminals. Lastly, we then must model the process by which this current transient is represented as a voltage wave traveling down a microstrip line as it is this wave that is sampled in electro-optic experiments of this sort. Once the models are developed they then are to be used in conjunction with actual experiments in probes of our understanding of carrier transport on the subpicosecond scale. The goal of the Arizona State University effort was the development of models for all three of these steps.

Status of Research

During the first portion of the first year our efforts centered on the transformation of optical pulse data into a set of electron-hole pair generation events which are distributed over the transmission line gap in both space and time. As the transport model to be used in the second step is a Monte Carlo model, we chose to use Monte Carlo techniques for this portion as well. An ensemble of incident photons is chosen which represents both the spectral and temporal distribution of the pulse by applying the same rejection techniques commonly used to model the distribution of scattering angles in various scattering events in transport Monte Carlo studies. The location in the gap along the surface is similarly selected by using a description of the pulse shape function, most generally a Gaussian function. The penetration depth into the sample can be selected by using the photon wavelength to select an appropriate optical absorption coefficient. The penetration depth then is an exponentially distributed function with this parameter serving as the mean penetration depth. This problem is identical with the statistical distribution of free flight times between scattering events in transport studies and the same techniques were used here to solve the optical penetration problem. In later efforts we extended these models to systems in which the conduction band model consisted of a three valley model while three valence bands (heavy hole, light hole and split-off bands) were used. In the final stages of the effort, the role of optical polarization in selecting carrier k-vectors was studied.

The simplest approach to understanding the potential for using such experiments as that of Hammond or Mourou et al. for studying transient carrier transport is to perform a Monte Carlo study. A set of valence bands are assumed and carriers are photogenerated out of these bands into the conduction bands by photons of a specified wavelength. A spatially uniform field is assumed and one then studies the transient response of the photogenerated electrons in this field. Early results of this sort generated some controversy. It was argued on the basis of such Monte Carlo modeling [9] that no velocity overshoot could be produced using these wavelengths. We later however showed that within the range to which the parameters used in such models are established, it cannot be argued that no overshoot occurs [7]. This was the first time the role of parameter variations had been assessed in terms of these high speed photoconductive switching experiments.

The earliest result of our modeling effort is a previously unnoticed wavelength dependency in the initial rise of the photocurrent. We have called this a Jone-Rees effect [10] because it had already been labeled as such in a related situation faced in Gunn diode physics. It occurs whenever carriers are introduced (either by intervalley scattering in a Gunn diode or by photogeneration as occurs here) near the energy threshold for intervalley scattering in the Gamma valley, provided an electric field is present (as is the case in both Gunn diodes and in photoconductivity). This should create a bias dependency in "short wavelength" transient photoconductive experiments but not in ones in which "long wavelengths" are used. Such a wavelength dependent delay may have been experimentally seen [6,7].

The experiments generally operated in a high excitation regime. We investigated the possibility that high excitation effects such as hot phonons and electron-hole interactions might significantly alter the predicted responses. Both of these possibilities were incorporated into the Monte Carlo code and we found that they do not significantly alter the general features of the transient response [11,12]. There are changes in this initial response associated with the polarization of the optical pump pulse which while not dramatic may be observable as well [13]. At the outset of this program we faced a difficulty in modeling the electron-hole interaction. While there had been a great deal of effort at developing good Monte Carlo models for electron transport in GaAs, holes had been neglected. They however cannot be neglected here. The development of a good hole model was the another main effort of the program which was successfully completed [14]. The hole model clearly shows that, as expected, hole currents should be much smaller than electron currents in these systems. We additionally noted that there was no data, either experimental or theoretical, on the field dependency of the steady state hole coefficient. A side result of this program was the development of such data [14].

In such experiments and in some of the associated work on device characterization the ability to predict the time behavior of a circuit is important. A quantitative comparison between theory and experiment calls in particular for the ability to make such calculations for systems which do not necessarily have a well-known equivalent circuit representation. We have developed techniques where a linear two-port whose S-parameters are well known in the frequency domain can be directly modeled in the time domain without any intermediate assumed circuit being required. The solution method allows us to solve for the time-domain response of a switched transmission line. We incorporated a transient photoconductor into this solution and applied it to the experiments of interest. This photoconductor model consisted of a uniform-field Monte Carlo electron model excited by a laser pulse as described above. The field varied in time in accordance with the voltage produced across the gap by the transmission line solution. A cold gap capacitance was included as well. The results indicated that the circuits were capable of producing voltage waveforms that closely resembled an underlying transient photocurrent waveform [7].

Even with such a model one asks about how an equivalent circuit can be constructed for the subpicosecond risetimes exhibited experimentally. Late in the program we began an interaction with Dr. Samir El-Ghazaly in which, for the first time, a Monte Carlo code is coupled directly with a transient numerical solution to Maxwell's equations in three dimensions. This now provides us with models which can directly predict the actual electro-optical shift in the polarization of the probe beam. [15-19].

There is one last problem faced in all such models. A Monte Carlo model is a particle based model and all the particles in the model eventually reach the edges of the region being simulated. In a model of conductivity, at least some of the these edges must allow the carriers to leave. If a process by which carriers are re-injected is not included, then eventually one is simulating an empty box. This is particularly complicated in a transient situation such as that of interest here as then it is not true that the number of carriers present in the system is constant. We therefore developed a novel extension of ideas by which charge is assigned to carriers in a Monte Carlo model (for purposes of calculating fields) which allows us to satisfy the appropriate conservation laws [20].

A brief summary of the overall program is that it resulted in the development of the first subpicosecond experiments on photoconductivity; clarified the role that transient hot carrier transport plays in such experiments; showed that in principle they can be used to provide a time domain experimental study of transient hot carrier transport; and resulted in a particularly rich Monte Carlo code for relating the transient response of a highly excited, photogenerated, bipolar plasma to the electromagnetic field structures produced on a transmission line structure.

References

1. J.G. Ruch, IEEE Trans. Electron Devices, ED-19, 652 (1972)
2. G. Mourou, K. Meyer, J. Whitaker, M. Pessot, R. Grondin and C. Caruso in Picosecond Optics and Optoelectronics II, Ed. F.J. Leonberger, C.H. Lee, F. Capasso and H. Morkoc, Springer-Verlag, Berlin, 1987
3. R.B. Hammond, Physica B, 134, 475 (1985)
4. D.H. Auston, IEEE J. Quantum Electronics, QE-19, 639 (1983)
5. J.A. Valdmanis, G.A. Mourou and C.W. Gabel, IEEE J. Quantum Electronics, QE-19, 664 (1983)
6. K.E. Meyer, M. Pessot, G.A. Mourou, R. O. Grondin and S. Chamoun, Appl. Phys. Letters, 53, 2254 (1988)
7. S.N. Chamoun, R. Joshi, E.N. Arnold, R.O. Grondin, K.E. Meyer, M. Pessot and G.A. Mourou, J. Appl. Physics, 66, 236 (1989)

8. K.E. Meyer and G.A. Mourou in Picosecond Electronics and optoelectronics, edited by G.A. Mourou, D. Bloom and C. Lee, Springer, Berlin (1985)

9. A. Evan Iverson, G.M. Wysin, D.L.Smith and A. Redondo, Appl. Phys. Lett., 52, 2148 (1988)

10. R.O. Grondin and M.J. Kann, Solid State Electronics, 31, 567 (1988)

11. R. Joshi, S. Chamoun and R.O. Grondin in OSA Proceedings on Picosecond Electronics and Optoelectronics Conf., Edited by T.C.L. Gerhard Sollner and D.M. Bloom, Vol 4, published by the Optical Society of America, Washington D.C., 1989

12. R. Joshi and R.O. Grondin, J. Applied Physics, 66, 4288 (1989)

13. R. Joshi, R.O. Grondin and S. El-Ghazaly, submitted for publication

14. R. Joshi and R.O. Grondin, Applied Physics Letters, 54, 2438 (1989)

15. Yliqun Lu, R. Joshi, S. El-Ghazaly and R.O. Grondin, Solid State Electronics, 32, 1297 (1989)

16. S. El-Ghazaly, R. Joshi and R.O. Grondin, to be published in IEEE Trans. Microwave Theory and Techniques

17. R.O. Grondin, R. Joshi and S. El-Ghazaly, to be presented at Ultrafast Laser Probe Phenomena in Bulk and Microstructure Semiconductors III, SPIE 1990 Symposium on Advances in Semiconductors and Superconductors, San Diego, March 1990

18. K.M. Connolly, S.M. Ghazaly, R.O. Grondin and R.O. Joshi, to be presented at the IEEE MTT-S Inter. Microwave Symp., 1990

19. K.M. Connolly, S.M. Ghazaly, R.O. Grondin and R.O. Joshi, to be presented at the XXIIIrd General Assembly of the Inter. Union of Radio Science, Prague, Czechoslovakia. August 28 to Sept. 5 1990

20. R. Joshi and R.O. Grondin, Solid State Electronics, 32, 1813 (1989)

Publications and Presentations

1. G. Mourou, K. Meyer, J. Whitaker, M. Pessot, R. Grondin and C. Caruso, "Ultrafast Optics Applied to Modern Device Research," in Picosecond Optics and Optoelectronics II, Ed. F.J. Leonberger, C.H. Lee, F. Capasso and H. Morkoc, Springer-Verlag, Berlin, 1987

2. R.O. Grondin and M.J. Kann, "Transport Correlation Coefficients and Photoconductive Switching," presented at the Fifth Conference on Hot Electrons in Semiconductors, refereed proceedings published in Solid State Electronics, Vol. 31, No. 3/4, pp. 567-570, 1988

3. K.E. Meyer, M. Pessot, G.A. Mourou, R. O. Grondin and S. Chamoun, "Subpicosecond Photoconductivity Overshoot in Gallium Arsenide Observed by Electro-Optic Sampling," Appl. Phys. Letters, Vol. 53, No. 23, pp. 2254-2256, Dec. 1988

4. R. Joshi, S. Chamoun and R.O. Grondin, "Electron-Hole Effects on the Velocity Overshoot in Photoconductive Switches," in OSA

Proceedings on Picosecond Electronics and Optoelectronics Conf., Edited by T.C.L. Gerhard Sollner and D.M. Bloom, Vol 4, pp. 147-152, published by the Optical Society of America, Washington D.C., 1989

5. R. Joshi and R.O. Grondin, "Monte Carlo Analysis of High Field Hole Diffusion Coefficients in Nondegenerate GaAs,", Applied Physics Letters, Vol. 54, No. 24, pp. 2438-2439, 12 June 1989

6. S.N. Chamoun, R. Joshi, E.N. Arnold, R.O. Grondin, K.E. Meyer, M. Pessot and G.A. Mourou, "Theoretical and Experimental Investigations of Subpicosecond Photoconductivity," J. Appl. Physics, vol. 66, No. 1, pp. 236-246, 1 July 1989

7. R. Joshi and R.O. Grondin, "A Self Consistent Monte Carlo Approach for the Transient Response of Laser Excited Photoconductive Circuits," Solid State Electronics, Vol. 32, No. 12, pp. 1813-1818, 1989

8. Yiqun Lu, R. Joshi, S. El-Ghazaly and R.O. Grondin, "Time Domain Finite Difference Study of Hot Carrier Transport in GaAs on a Subpicosecond Scale," Solid State Electronics, Vol. 32, No. 12, pp. 1297-1302, 1989

9. R. Joshi and R.O. Grondin, "Hot Phonon and Electron-Hole Scattering Effects on the Transient Transport of Photogenerated Electrons in GaAs," J. Applied Physics, Vol. 66, No. 9, pp. 4288-4294, 1 November 1989

10. S. El-Ghazaly, R. Joshi and R.O. Grondin, "Electromagnetic and Transport Considerations in Subpicosecond Photoconductive Switch modeling," to be published in IEEE Trans. Microwave Theory and Techniques

11. R.O. Grondin, R. Joshi and S. El-Ghazaly, "Physical Modeling of Ultrafast Electrical Waveform Generation and Characterization," to be presented at Ultrafast Laser Probe Phenomena in Bulk and Microstructure Semiconductors III, SPIE 1990 Symposium on Advances in Semiconductors and Superconductors, San Diego, March 1990

12. K.M. Connolly, S.M. Ghazaly, R.O. Grondin and R.O. Joshi, "Coupling Maxwell's equation Time Domain Solution with Monte Carlo Technique to Simulate Ultrafast Optically Controlled Switches," to be presented at the IEEE MTT-S Inter. Microwave Symp., 1990

13. K.M. Connolly, S.M. Ghazaly, R.O. Grondin and R.O. Joshi, "Study of Ultrafast Pulse Generation and Characterization," to be presented at the XXIIIrd General Assembly of the Inter. Union of Radio Science, Prague, Czechslovakia. August 28 to Sept. 5 1990

Professional Personnel

Dr. Robert O. Grondin began this project as an assistant professor and is now an associate professor of Electrical and Computer Engineering at Arizona State University and the principal investigator of the present effort. He received the BS, MS and Ph.D. degrees in Electrical Engineering from the University of Michigan. He was a post-doctoral fellow at Colorado State University prior to his acceptance of his present faculty position in 1983. In 1985 he was named a Presidential Young Investigator by the National Science Foundation.

The following individuals received masters degrees in electrical engineering with a dissertation supported by this program:

Christopher Caruso

Eric Arnold

Sleiman Chamoun

Ms. Deanna Chang, a female US citizen majoring in Electrical Engineering, was employed as a work-study student during her undergraduate program.

Dr. Ravindra Joshi, now on the faculty of the Department of Electrical Engineering of Old Dominion University was employed as a post doctoral fellow while working on this program.

Interactions

A strong interaction has developed between this effort and the companion experimental efforts which continues to this day. The optical work is now done either by Mourou at the University of Michigan or by Dr. Kevin Meyer, now at the Cavendish Laboratory of Cambridge University. His interaction with Dr. Grondin is supported by a NATO travel grant at present. Dr. Grondin, in conjunction with Dr. Ronald Roedel, is involved in producing transmission line structures on GaAs substrates which are selectively doped to produce nin, pip or pin type of gaps.

During the Boston Hot Carriers Conference in 1987, Kevin Meyer, Ted Norris (now at the University of Michigan) and Robert Grondin all noted that no one was performing transient absorption experiments using biased samples. We have begun an effort at the development of such an experiment. We have collaborated with Mohammed Osman, originally with Scientific Research Associates and now with Washington State University, on this problem.

We continue to interact with Dr. Joshi and with Dr. El-Ghazaly. A proposal is now pending with the Naional Science Foundation which would continue this collaborative modeling effort.